International Conference on FRACTURE

A Conference Report by C. C. Hsiao

In 1963 the writer and several other scientists from different places - including Tokyo, Japan, Moscow, USSR, and a couple of eastern states, USA - discussed the need for holding an international conference on strength and fracture in Japan. Some preliminary steps were subsequently taken to plan such a conference. It was recognized that the arrangement of an international meeting in Japan would not be an easy undertaking, since many people interested in the conference were not themselves in Japan. However, a piece of good news came shortly afterwards. Professor Takeo Yokobori of Tohoku (Northeast) University, Japan, and many other Japanese scientists, assisted by a number of foreign scientists were actively interested in and were organizing a similar international conference on fracture.

Because of Professor Yokobori's endless efforts and under the auspices of many Japanese scientific societies, the International Conference on Fracture finally took place on September 12-17, 1965. The location was the two halls, Aobanoma (green leaves) and Aoinoma (hollyhock tree) in Sendai Hotel, Sendai City, on the east coast of the largest island, Honshu, of Japan. According to the announced coverage, both macroscopic and microscopic aspects of fracture would be

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considered in the conference. The program, printed in English, included the following areas of interest:

A. Mathematical, physical and continuum mechanical theories;

B. Atomistic, microstructural and macroscopic mechanics;

C. Strength and fracture of non-metallic materials;

D. Fatigue and fracture with emphasis on microscopic behavior;

and

E. Environmental effects, high pressure, high temperature, high strain rate, radiation damage, etc.

Sunday afternoon, September 12, close to one hundred foreign scientists from various parts of the world registred together with more than two hundred Japanese scientists. A gala opening cocktail party as well as marvelous traditional Japanese dances provided a wonderful opportunity for participants to get better acquainted.

The opening ceremony began at 9 a.m. Monday, September 13, with an introductory speech by Professor Yokobori and a welcome address by the Mayor of Sendai. Two simultaneous technical sessions followed immediately after the brief preliminaries. In one of the sessions Prof. E. Kröner proposed a continuum theory dealing with the range of atomic cohesian forces. Subsequently Prof. K. Kondo of Japan discussed the geometrical approach to the micromechanics of fracture. While one session was concerned with continuum theories, the other session dealt with fatigue fracture and observations of fracture surfaces. After a pause for refreshments, the two parallel sessions were continued. Several reports regarding dislocations and

crack propagation were discussed from late in the morning until noon. After lunch research results obtained by both Japanese and foreign scientists on investigations of the mechanism of fracture were reported. The individual sessions went smoothly and systematically according to the printed program. The only exceptions were that several scheduled papers authored by scientists from USSR had to be canceled. However, several Russian authors did arrive to attend the Conference at the end of the last day of the technical session. Professor S. N. Zhurkov of the Physical-Technical Institute of the Academy of Sciences of the USSR, Leningrad, USSR, presented his special lecture on the kinetic concept of strength of solids at the closing of the conference. Because of the interesting nature of his work, a brief account will be given later.

The second day of the technical session started with a special lecture by Professor B. L. Averbach on micro and macro crack formation. In his presentation, Professor Averbach outlined the mechanism of micro crack formation and the associated critical value of the crack extension force to provide the basis for a fracture safe design criterion. Following this lecture, again two parallel technical sessions were held. One of the sessions was occupied with the presentation of papers primarily concerned with continuum mechanics studies of fracture problems. The other session, in the meantime, dealt essentially with microscopic aspects of fracture phenomena.

The principal feature of the third day began with a special lecture on the subject of initiation and growth of viscoelastic fracture by Professor M. L. Williams. His interesting work pointed out the possibilities of extending Griffith theory in fracture mechanics for brittle materials to materials having dominating time dependent flow characteristics as well as viscous dissipation mechanisms. Thus the previous Griffith critical stress results for fracture could be cast into a similar form as

$$\sigma_{cr} = K\left(\frac{E}{\ell}\sum_i T_i\right)^{1/2}$$

where K is a constant, E the material modulus and ℓ the crack length and T_i represents the individual energy quantities associated with the particular dissipation processes for brittle, ductile and viscoelastic materials. In addition, several polymer reports were also presented that day at one of the technical sessions together with papers concerned with studies of glass, cement and fatigue of metals.

During the last day of the conference, various aspects of fracture, such as growth of fatigue crack, environmental effects on fracture, strain rate effects on deformation and failure, etc. were considered. Near the end of the technical sessions, Professor Zhurkov arrived and presented his special lecture on the kinetic concept of strength of solids. For clarity Professor Zhurkov asked Professor Williams to present part of his paper. In his report first of all the kinetic nature of the fracture process of solids was pointed out. He

supported his claim by reviewing his earlier experimental studies and findings[1] and considered the thermofluctuation mechanism of fracture. According to his report it has been easy to demonstrate that the relationship between the lifetime or time to break t_m, the applied constant simple tensile stress σ and the absolute temperature T could be written in the form of a kinetic operation:

$$t_m = t_o e^{\frac{U_o - \gamma\sigma}{KT}} \qquad (1)$$

where K is the Boltzman's constant, t_o, U_o and γ are material constants. This formula did not represent just an ordinary emperical relationship but possessed a significant physical process of destruction in stressed solids in general. For various kinds of solids such as silver chloride, aluminum, polymethyl methacrylate, etc. t_o was found to be about 10^{-13} sec. The reciprocal of t_o coincided with the natural oscillation frequency of atoms in solids. The quantity U_o was interpreted as the magnitude of the energy barrier determining the probability of breakage of the bonds responsible for strength. Experimental data collected for lattice solids indicated that U_o fitted well with the energy of sublimation or the binding energy of atoms in the crystal lattice in metals. Similarly for polymers, U_o corresponded with the energy of breakage of chemical bonds in macromolecular chains. The

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[1] C. C. Hsiao, Physics Today, 12, 30 (1959)

$$t_m = C_2 e^{-\alpha_2 \sigma} \tag{3}$$

where $C_2 \equiv t_o e^{U_o/KT}$ and $\alpha_2 \equiv \frac{\gamma}{KT}$ at a given temperature T are constants.

If the lifetime or time-to-break of a stressed polymer was completely determined by the rate of accumulation of the ruptured bonds, then one might expect the exponents α_1 and α_2 to be equal. In this case the lifetime of the specimen and the rupture rate of the bonds in the specimen under a constant stress at a given temperature should be related by the equality

$$v t_m = C_1 C_2 = \text{constant} \tag{4}$$

An experimental verification of this relation for nylon fibres, at room temperature, at 50°C and at -50°C has shown a good agreement with the theoretical prediction. Thus the EPR-method proved to be a very effective tool in obtaining a direct confirmation of the kinetic nature of polymer fracture process.

However, in Prof. Zhurkov's report, he also indicated the deviation from (1) when small stresses were involved in experimental studies. The reason for such deviation which was found to be common for different solids has not yet been elucidated. Besides this principal deviation one more violation of the general linear law between the logarithm of time-to-fracture and the applied constant stress in the given general

kinetic equation (1) was also frequently observed. This was not interpreted as a principal nature and was claimed as being associated with the instability of materials in mechanical tests. Stabilization of the structure would result, as a rule, in a straightening out of the nonlinear relationship between $\ln t_m$ and σ, so that its total consistency with the general kinetic equation (1) would be obtained.

With regard to this point Professor C. C. Hsiao had presented some analytical results during the second day of the conference. In his report the kinetic process was considered in the study of the ultimate behavior of solids. It appeared that on somewhat similar basis, the deviation of the linearity between the logarithm of time to fracture of a solid subjected to a simple tensile stress would result while linear relations could only be obtained under large stresses. Prof. Hsiao had an opportunity to discuss this subject with Prof. Zhurkov in Tokyo one evening. It might be of interest to give a brief account of this information here, as the reported work of Hsiao and Zhurkov may be considered supplementary to each other. The true mechanism of fracture of solids may be revealed from these studies.

Prof. Hsiao reported his findings on the basis of utilizing the statistical theory of the absolute reaction rate[2]. The mathematical model used was a matric of oriented elements or bonds, whether they be primary or secondary, embedded

[2] C. C. Hsiao, J. Appl. Phys. 30, 1492 (1959)

randomly in an arbitrary domain. If f represented the fraction of unbroken elements per unit solid angle, then the rate of change of f can be written as

$$\frac{df}{dt} = K_r\left(\frac{1}{4\pi} - f\right) - K_b f \tag{5}$$

where $K_r = \omega_r e^{-(U/RT + \rho\psi)}$ is the rate of reformation of broken elements, ω_r the frequency of motion of broken elements. U is the original potential energy barrier to be crossed between two equilibrium states, R is a universal constant, T is absolute temperature, ρ is a material constant for the system and $\psi(t)$ is the stress subjected by the elements; similarly $K_b = \omega_b e^{-(U/RT - \beta\psi)}$ where K_b and ω_b are respectively the rate of rupturing and frequency of motion of unbroken elements, and β is a modification constant. After a stress $\sigma(t)$ is applied to the system as a whole, the energy barrier for parallel elements became modified to $U/RT - \beta\psi(t)$ in the direction of stressing and to $U/RT + \rho\psi(t)$ in the opposite direction. The time-dependent fracture of any medium can be studied by solving (5), from which

$$f = \frac{1}{4\pi} e^{-\int_o^t (K_r+K_b)dt}\left[\int_o^t K_r e^{\int_o^t (K_r+K_b)dt}\, dt + \frac{1}{2}\right] \tag{6}$$

assuming that $K_r = K_b$ when there is no modification in the energy barrier. For simplicity consider a fully oriented system, the stress function $\psi(t)$ in each element would be given by

$$\psi(t) = \frac{\sigma(t)}{f(t)} \tag{7}$$

Again for simplicity the fracture under the influence of a constant stress σ was considered and an assumption that the fracture strength was associated with a limiting value $\psi_m = \psi(t_m)$ beyond which every element oriented in the direction of applied stress would break. Then at a specific time-to-break t_m

$$\psi(t_m) = \frac{\sigma}{f(t_m)} \tag{8}$$

Now returning to (6), for a large value of stress ψ_m, K_b can be shown to be very large compared with K_r. Therefore to a first approximation, (6) may be reduced to the following form

$$f(t) = \frac{1}{8\pi} e^{-\int_o^t \omega_b e^{-U/RT - \beta\psi(\tau)} d\tau} \tag{9}$$

From (7) and (9) one could write

$$\psi(t_m) = 8\pi\sigma e^{\omega_b e^{-\frac{U}{RT}} \left[\int_o^{t_m} e^{\beta[\psi(0)+\psi^1(0)\tau+\ldots]} d\tau\right]} \tag{10}$$

where t_m is the time to fracture for a constant applied stress σ. From this it was found that $\psi(0) = 8\pi\sigma$ together with $\psi(t_m)=\psi_m$

$$\ln\frac{8\pi\sigma}{\psi_m} + \omega_b e^{-\frac{U}{RT}} e^{8\pi\beta\sigma} e^{\ln t_m} = 0 \qquad (11)$$

Remember that this expression is only true for large values of σ. In this case it is likely that

$$e^{8\pi\beta\sigma} >> \ln \frac{8\pi\sigma}{\psi_m} \qquad (12)$$

Then (11) can be approximated to show a linear relation between the logarithm of time $\ln t_m$ and the constant applied fracture stress σ

$$\sigma \cong \frac{1}{8\pi\beta} \left(\frac{U}{RT} - \ln\omega_b t_m\right) \qquad (13)$$

This can be put in the following form as

$$t_m = \frac{1}{\omega_b} e^{\frac{U}{RT} - 8\pi\beta\sigma} \qquad (14)$$

which is similar to (1) given by Prof. Zhurkov. Assuming that the above general formulation and approximations in the analysis are acceptable, then (14) cannot be said to represent a general kinetic process in fracture without qualifications. The linear relations (14) can be obtained only if the range of values for σ is sufficiently large. When values of σ are small, the logarithmic term in (11) becomes important. By including this term, one can easily put (11) in the following form:

$$t_m = \frac{1}{\omega_b} \ln \frac{\psi_m}{8\pi\sigma} e^{\frac{U}{RT} - 8\pi\beta\sigma} \qquad (15)$$

Comparing this equation with (1), it is seen that t_o should be replaced by a function of the applied stress σ instead of being a constant as suggested by Prof. Zhurkov. In fact, even (15) cannot be regarded as precise when σ becomes very small. In that case K_r and K_b will be comparable and (6) must be consulted if a consistent kinetic process for fracture under all ranges of applied stress is to be maintained.